The Atacama Cosmology Telescope

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Abstract. The Atacama Cosmology Telescope (ACT) project is described. This multi-institution collaboration aims to produce arcminute-resolution and micro-Kelvin sensitivity maps of the microwave background temperature over 200 square degrees of the sky in three frequency bands. We give a brief overview of the scientific motivations for such a map, followed by a design outline of our six-meter custom telescope, an overview of our proposed bolometer array detector technology, and site considerations and scan strategy. We also describe associated optical and X-ray galaxy cluster surveys.

SCIENTIFIC MOTIVATION

With results from WMAP in hand, it is clear that the near-term future of microwave background measurements will be primarily a push towards smaller angular scales and polarization. As described at this meeting, many small-scale experiments are currently underway, under construction, or in the planning stage. This paper describes an ambitious proposed collaboration, the Atacama Cosmology Telescope, which aims to combine new bolometer array technology with a custom-designed six-meter telescope to produce an instrument with a notable combination of sensitivity, angular resolution, and control of systematic errors. Current information about the experiment is available at http://www.hep.upenn.edu~angelica/act/act.html. Before detailing the experimental and observational aspects of this effort, we give a brief summary of the main scientific questions we aim to address, which are covered in more detail elsewhere in these proceedings (see also [1]).

At angular scales smaller than around 4 arcminutes, corresponding to multipoles $l > 3000$, nonlinear contributions begin to dominate the total microwave background temperature anisotropies. The major sources of temperature fluctuations on these scales include the Sunyaev-Zeldovich effect, the Ostriker-Vishniac effect, and gravitational lensing. All of these effects arise both from individual clusters of galaxies and from the large-scale matter distribution.

The largest amplitude signal will come from the thermal SZ galaxy cluster distortions. We expect to compile a large catalog of clusters selected by their SZ signals, which provides a cleaner cluster selection criterion than flux-limited optical or X-ray surveys. This catalog will be well-suited to measuring the cluster number density as a function of mass and redshift, which is a sensitive probe of the growth rate of structure since redshift $z = 1$; in turn, the structure growth rate constrains dark energy and neutrino masses. We also expect to place significant constraints on cluster masses and peculiar velocities via their kinematic SZ and gravitational lensing signatures. For the diffuse signals, we aim

to detect gravitational lensing of the microwave background and construct a projected mass map on scales of 15 arcminutes. We expect to have sufficient sensitivity to detect the Ostriker-Vishniac effect, which is sensitive to the redshift and spatial variation of reionization, and the Rees-Sciama effect, which is sensitive to the non-linear evolution of gravitational potentials.

ACT will provide a measurement of the power spectrum on all scales from $l = 200$ to $l = 10000$, probing the primordial fluctuation spectrum for departures from a power law or for features; either could arise from non-minimal models of inflation. Having a single experiment which probes a wide range of angular scales with good control of systematics is crucial for uncovering small departures from perfect power law primordial spectra.

ACT's scan strategy results in a significant area of the survey being in the galactic plane. A variety of interesting topics in galactic astrophysics can be addressed with such a map, particularly properties and distribution of dust.

TELESCOPE

The stringent control of systematic errors necessary to attain temperature measurements at 1 μK sensitivity drives many aspects of our telescope design. A schematic illustrating important features is shown in Fig. 1. The primary reflector has a diameter of 6 meters, producing diffraction-limited resolution of approximately 1.7 arcminutes at 150 GHz and 0.9 arcminutes at 270 GHz. A preliminary design configuration gave a clear aperture by employing three off-axis, aspherical mirrors in a double-Gregorian configuration; the final optical design will be somewhat different. The resulting field of view is wide and flat, with minimal side-lobe response and telescope offset. Additional reimaging optics and a cold Lyot stop will be contained within the cryostat containing the detectors described below.

The telescope is low to the ground, allowing large shields to reduce ground pickup. The entire optical path will maintain polarization information; while our initial plans do not include polarized detectors, our design will allow future detector upgrades.

The telescope sits on a large bearing; the entire telescope structure, including a ground screen not shown in the figure, will rotate in azimuth. This strategy guarantees that no reflecting or diffracting surfaces ever move with respect to the receiver, and thus any pickup through the near-field sidelobes will remain constant. The nominal observing elevation of the telescope is $45°$ with limited elevation control, but as explained below, the baseline observing strategy calls for a constant elevation so the same atmospheric depth is observed at all times.

The telescope will be remote controlled with data transferred via a radio downlink, since the Atacama site (described below) is at a high altitude. Such a scheme has been previously employed with the MAT/TOCO experiment [2] by members of our collaboration.
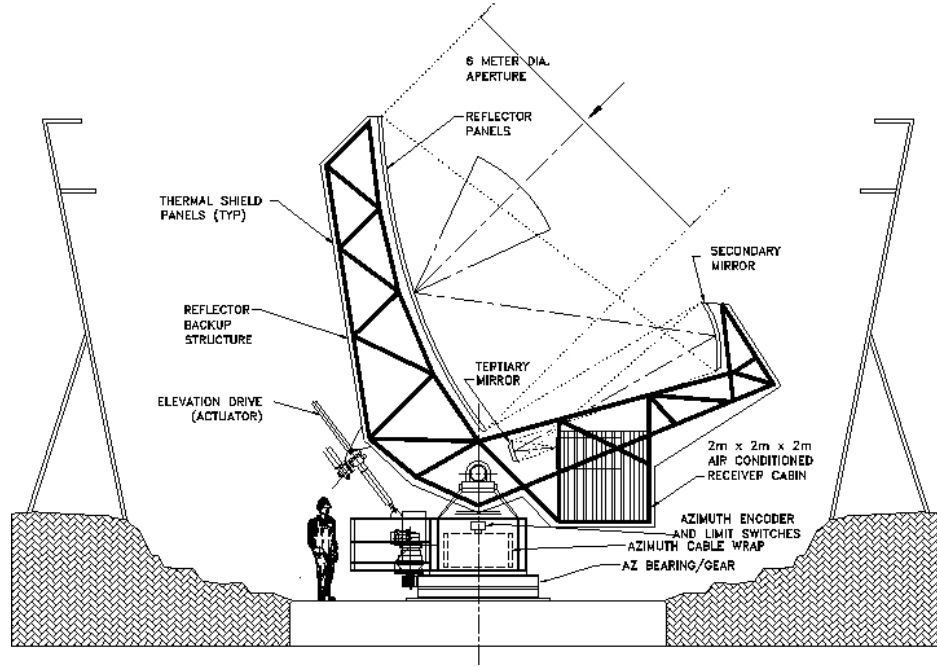
FIGURE 1. A schematic design for the Atacama Cosmology Telescope. For clarity of presentation, an additional ground screen which rotates in azimuth with the telescope is not shown. The final optical design of the telescope will be different.

DETECTORS

Current experiments employ arrays as large as roughly a hundred bolometers. The "camera" we propose as the receiver for the ACT telescope will employ three separate 32×32 arrays of 1 square-millimeter superconducting transition edge sensor (TES) bolometers [3, 4] on pop-up arrays . In recent years, Harvey Moseley and colleagues at Goddard Space Flight Center have developed a technology in which bolometers are packed into CCD-like arrays. Arrays have so far been fabricated for use at shorter wavelengths; see [5] for an overview of the 12×32 SHARC array which has been built for the Caltech Submillimeter Observatory. These detector arrays have a number of distinct advantages: (1) The array elements are close-packed, filling the focal plane; (2) The TES thermal time constant is ≤ 1.5 ms ($f_{max} \approx 110$ Hz), allowing rapid scanning of the arrays; (3) Each TES is intrinsically stable on time scales of 0.8 s ($f_{knee} \approx 0.2$ Hz); (4) The TES intrinsic electrical noise equivalent power is below 10^{-17} W/$\sqrt{Hz}$ at 265 mK physical temperature. The detector arrays will be maintained at temperatures near 270 mK using a combination of pumped ^{4}He and ^{3}He systems, with no consumable cryogens. To minimize the number of connections to the dewar, we plan to read out each array with a SQUID multiplexor [6] which has been developed by Kent Irwin's group at NIST.

We plan to observe three frequency bands simultaneously: a low frequency band centered around 145 GHz, a middle band around 225 GHz, and a high frequency band around 265 GHz; the width of each band will be 25 to 30 GHz. The middle frequency

band will straddle the null of the thermal SZ effect, allowing a clear identification of SZ galaxy clusters via their signal in all three frequency bands. Our target sensitivity per bolometer is 300 μK sec$^{1/2}$ in the lowest frequency band, 500 μK sec$^{1/2}$ in the middle band, and 700 μK sec$^{1/2}$ in the high frequency band.

SITE CHARACTERISTICS

The telescope will be sited on Cerro Toco, in the Atacama desert of the Chilean Andes, at an altitude of 5200 meters. The site is the same one used previously for the MAT/TOCO experiment [2], and is a few kilometers from the ALMA [7] and CBI [8] site. The weather and atmosphere at these sites is well characterized; atmospheric measurements over several years at a frequency of 225 GHz are available at the ALMA web site, http://www.alma.nrao.edu. The MAT/TOCO experiment also operated at the ACT site during 1997 and 1998 and made extensive atmospheric measurements; the median measured sky temperature during these observing runs was approximately 9 K at 150 GHz.

The atmospheric characteristics of our site are comparable to those of the South Pole, where several other small-scale microwave background measurements will be sited. The ACT site is at a significantly higher altitude, but usually has a higher amount of precipitable water vapor. While the South Pole has a lower yearly-averaged atmospheric opacity than the ACT site, well-understood annual and diurnal fluctuations at the Chile site bias this comparison. For roughly 8 months per year, the opacities at the two sites are comparable, and when night-only data is considered, the opacity in Chile is actually better than that at the South Pole 25% of the time. ACT will observe only during the 6 months of each year in which atmospheric conditions are most favorable.

We have used the calculations of Lay and Halverson [9] for the expected noise contribution from atmospheric emission to a scanned beam to estimate the atmosphere-induced temperature fluctuations for ACT as a function of angular scale. We find that for angular scales smaller than about 25 arcminutes, the atmospheric noise will be smaller than our receiver noise. For this estimate, we have used the best 50% of all the atmospheric data.

SCAN PATTERN AND PROJECTED SENSITIVITY

The major advantage of the ACT site is geographic. A change in observing elevation by 1 degree can result in a change in the effective atmospheric emission of tens of milli-Kelvin due to the changing atmospheric column density, which is a factor of 10^4 larger than the fluctuations we are trying to measure. To control systematic errors and striping in the maps, observations at constant elevation are highly beneficial. While a scan strategy has not been finalized, we anticipate something close to the following. The site is at $23°$ south latitute; our first observations are planned at the nominal fixed elevation of $45°$. As an example strategy, we scan the entire telescope $\pm 1.5°$ in azimuth centered on one of two azimuths at $207°$ and $153°$. This constant-elevation scan pattern

over 24 hours results in a cross-linked pattern over an annulus $1.7°$ wide and $140°$ long. The cross-linking facilitates a robust map solution and allows for systematic checks. Approximately half of the survey region will be through the galactic plane, while the other half, around 100 square degrees, will be suitable for cosmological analysis. Primary calibration will be via comparison with the WMAP maps; we will also have the capability to track in elevation for observation of secondary calibration sources.

The combination of optical geometry, detector configuration, and scan strategy results in each sky pixel being observed on 6 distinct time scales: (1) Each detector pixel scans across a sky pixel in 0.02 seconds; (2) The entire detector array scans across a sky pixel in 0.4 seconds; (3) Each complete scan of the telescope is completed in 3 seconds; (4) A given sky pixel drifts through the size of the beam in 9 seconds; (5) A given sky pixel drifts throught the size of the field of view in 3 minutes; (6) A given pixel is observed at an interval of 7 hours as it rotates from one azimuthal chop region to the other. This chopping scheme is made possible by the fast response, sensitivity, and stability of the TES bolometers. Using the strong spatio-temporal filter provided by the scan strategy, we aim to solve for the celestial signal in the presence of atmospheric and instrumental fluctuations. Recall that the scan strategy is accomplished by moving the entire telescope, with the optical path kept fixed at all times.

We plan science observations only during half of the year corresponding to the most favorable atmospheric conditions. With the combination of telescope, detectors, and observation strategy described here, our target sensitivity can produce a map with 2 μK errors per $1.7'$ pixel over 200 square degrees.

ASSOCIATED GALAXY CLUSTER SURVEYS

ACT will identify on the order of a thousand galaxy clusters in the survey region (depending on the cosmological model), down to a limiting mass of around $2 \times 10^{14} M_\odot$ to arbitrary redshift. Use of this cluster catalog as a cosmological probe requires cluster redshifts. We plan to use the Prime Focus Imaging Spectrograph on the 11-meter Southern African Large Telescope (see http://www.salt.ac.za), currently under construction at the South African Astronomical Observatory, to obtain up to 400 cluster redshifts, along with galaxy velocity dispersions, over two years. By using a slit mask, SALT will be able to determine spectroscopic redshifts for 30 cluster galaxies simultaneously in 30 minute exposures for clusters at redshifts $z < 1$; the galaxy velocity dispersion will be determined along with the mean redshift, providing an independent estimate of cluster mass. Rutgers, which is a 10% partner in building SALT, has committed 10 nights of observing time per year to cluster follow-up observations. Additional spectroscopic redshifts as well as photometry will be obtained by our Chilean collaborators using various large telescopes.

We also plan to pursue X-ray imaging of a subset of clusters with the Chandra and XMM satellites, to obtain information on cluster gas temperatures and densities. X-ray measurements will provided estimates of cluster masses, densities, and temperatures, although subject to some systematic errors due to cluster substructure and departures from isothermality. Information from X-ray observations will help to establish the connection

between cluster SZ signals and cluster masses. High-resolution optical imaging with the Hubble Space Telescope would also provide a wealth of data for probing evolution of galaxies in clusters at a wide range of redshifts, and we would like to initiate such an observing program, if possible, once a reliable cluster catalog has been established.

CURRENT STATUS AND TIMELINE

ACT has been funded by the NSF beginning in January 2004. Much development work has already occurred, particularly in the areas of optical design, cryogenic design, and bolometer array testing. We anticipate that telescope construction will take two years and receiver design and fabrication 3 years, followed by two full seasons of observing. The SALT telescope and prime focus spectrograph are on budget and on schedule for first light in February 2005.

The next generation of microwave background measurements at unprecedented sensitivities are now on the horizon, making use of new technologies and past design experience. We anticipate that the Atacama Cosmology Telescope project described here will produce a high-fidelity map of the cosmic microwave background radiation at arcminute resolution and near micro-Kelvin sensitivities, opening the door to a number of new and interesting cosmological probes.

ACKNOWLEDGMENTS

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